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**UNITED STATES DEPARTMENT OF ENERGY  
UNIVERSITY CENTER OF EXCELLENCE  
FOR PHOTOVOLTAIC RESEARCH AND EDUCATION**

April 18, 2008

Bolko von Roedern  
National Renewable Energy Laboratory  
1617 Cole Boulevard  
Golden, CO 80401

Re: NREL Subcontract #ADJ-1-30630-12  
D.5.25

Dear Bolko,

This report covers research conducted at the Institute of Energy Conversion (IEC) for the period of November 1, 2007 to November 30, 2007, under the subject subcontract. The report highlights progress and results obtained under Task 4 (Si-based solar cells).

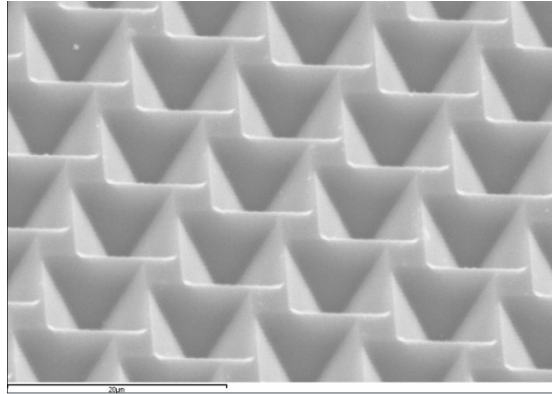
**Task 4 – Si based Solar Cells**

Surface Texturing and Passivation

High efficiency Si solar cells require a textured surface with an anti-reflection layer, to reduce reflection and increase light trapping, and a well-passivated surface, to reduce recombination and increase  $V_{OC}$ . The three processing sequences must be integrated together and be compatible with one another to achieve the full benefits. This section covers work performed at IEC to develop inverted pyramidal texturing on a planar (100) FZ wafer, followed by chemical cleaning of the surface and low temperature passivation.

The process of inverted texturing developed at IEC is as follows:

1. PECVD deposition of 20nm SiN sacrificial layer
2. Photoresistor is applied and pattern is defined by mask
3. Patterning using photolithography
4. 60s 1:9 buffered oxide etch (BOE) etching SiN to open texturing window and exposure of Si surface
5. 30% KOH solution with 2%IPA @ 50 degrees textures surface and gets desirable pattern

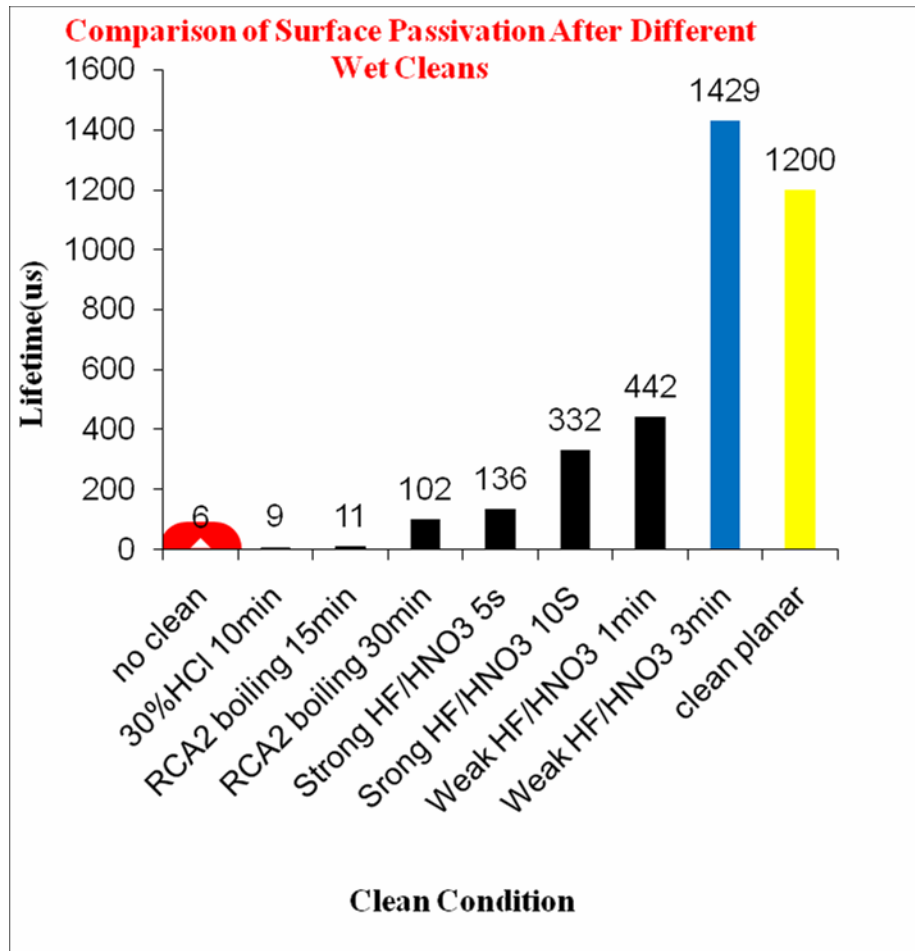


**Figure 1. SEM image of inverted pyramids**

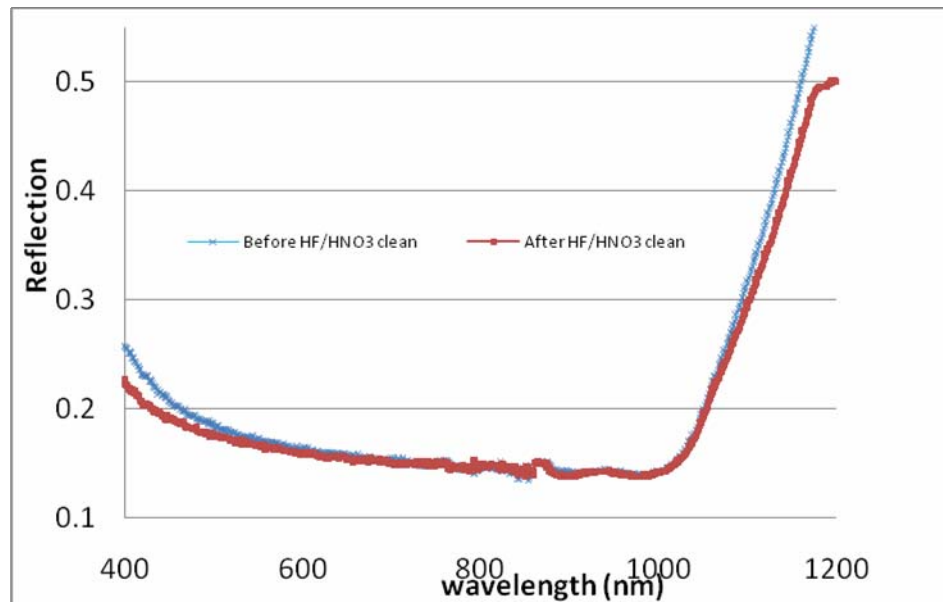
The resulted inverted pyramids as shown in Figure 1 give a reduced surface reflection. Surface passivation following etching is critical for a better solar cell design. IEC standard 10 nm intrinsic a-Si layer with  $H_2/SiH_4=2$  deposited by PECVD on a textured surface was ineffective as a passivation layer, yielding wafers with very low effective lifetime ( $\tau_{eff}$ ) of 5-6  $\mu s$ , which is comparable to a bare planar Si surface without passivation. This result indicated that the textured surface needed special treatment to remove any possible chemical damage, potassium contamination and surface stain induced prior to depositing a surface passivation layer.

Various chemical processes were used to treat the surface after texturing, then a standard intrinsic a-Si layer is applied for passivation and finally  $\tau_{eff}$  was characterized by the Sinton Lifetime QSS PCD method. The results are summarized as Figure 2. The control group is passivation on a clean planar wafer surface, indicated as the yellow column. The treatment consisting of dilute (1:19) HF:  $HNO_3$  demonstrated the most effective surface treatment. This is a more gentle solution compared with commonly used CP4 (Chemical Polish 4). It is more controllable and tends to be more anisotropic in etching, thus maintaining the original texture and hence having little effect on increasing the reflection after cleaning. Figure 3 compares the reflection on a bare Si texturing surface (without AR coating) before and after 1:19 HF:  $HNO_3$  clean. No surface reflection increase is observed.

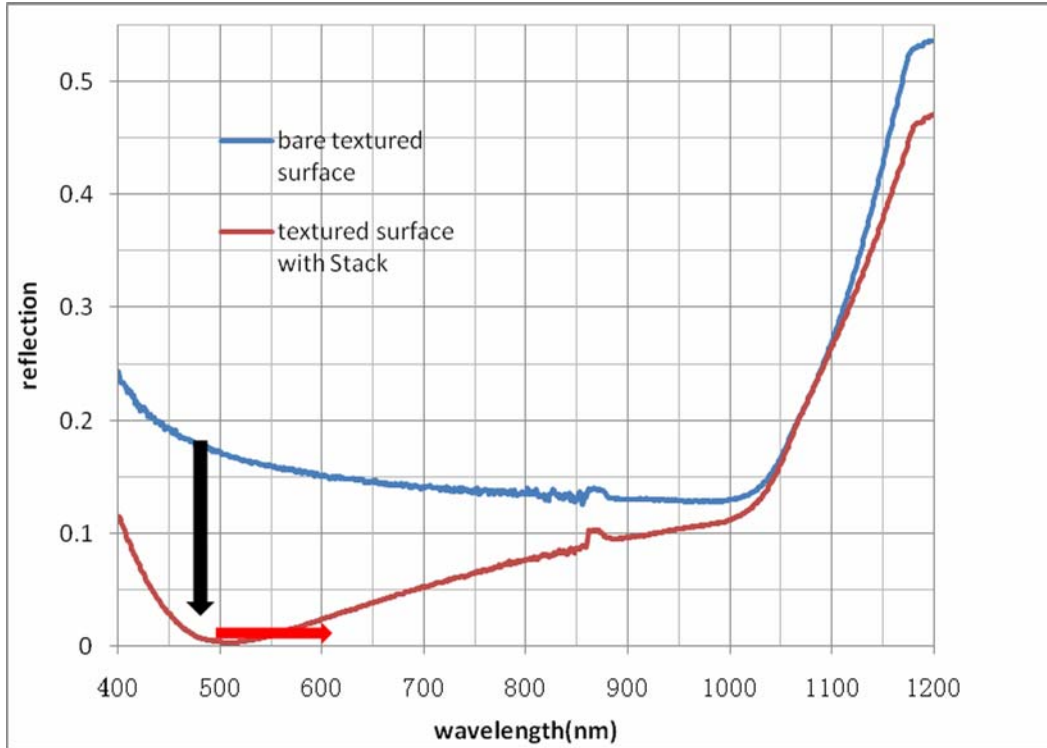
Finally, the AR coating and passivation must be integrated on the textured surface. An AR/passivation stack consisting of 80nm  $SiN_x$  layer on a 5nm standard intrinsic a-Si layer was deposited by PECVD. The surface reflection is shown in Figure 4. The reflection is reduced everywhere, notable to near zero around 500 nm as designed. The resulting surface recombination velocity was 20cm/s, which is very acceptable. Plans are underway to incorporate these process developments into a completed solar cell.



**Figure 2. Surface passivation vs. clean condition after texturing**



**Figure 3. Comparison of reflection from bare textured silicon (without AR coating)**



**Figure 4. The effect of stack structure on low surface reflection**

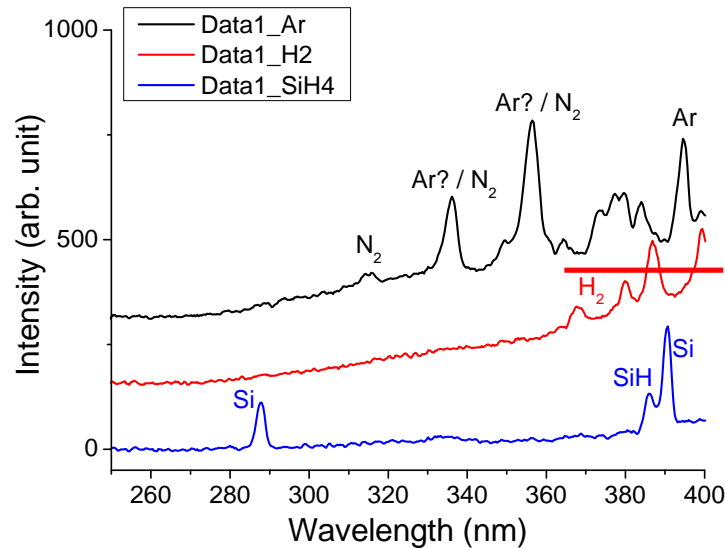
#### Effect of Real-Time Detection of Impurities by OES

We have observed from secondary ion mass spectroscopy (SIMS) studies of the amorphous silicon (a-Si:H) i-layer deposited in the MC System that the oxygen and nitrogen impurities in the film were disturbingly high:  $O \sim 1 \times 10^{20}$  and  $N \sim 1 \times 10^{19} \text{ cm}^{-3}$ . This included RF and DC plasma, with two different bottles of  $\text{SiH}_4$ , and was consistent over a 2 year period. The source of these impurities can be due to: (i) small atmospheric leak in the chamber; (ii) trace amount of impurities in the process gases; and/or (iii) impurities coming out from outgasing of the chambers at the deposition temperature. These impurities are known to act as either trapping or recombination centers in a-Si, hence to have a deleterious effect on the intrinsic layers used for passivation of c-Si cells or absorber layers in a-Si p-I-n cells. We have attempted to find the source of these impurities in the film by looking into plasma optical emission spectroscopy (OES) which provides information about the presence of excited atomic and molecular species. Kampas and Griffith (F. J. Kampas & R. W. Griffith, "Optical Emission Spectroscopy: Toward the Identification of Species in the Plasma Deposition of Hydrogenated Amorphous Silicon Alloys" Solar Cells 2 (1980), 385 – 400) studied OES in detail to detect trace amount of atmospheric impurities like  $\text{N}_2$ ,  $\text{O}_2$  and  $\text{H}_2\text{O}$  in the plasma and correlate with the impurity concentration in the deposited a-Si:H film. It was observed that  $\text{N}_2$  has a very high level of emission sensitivity but with low incorporation efficiency in the film. In contrast,  $\text{O}_2$  has weak emission but has an extreme reactivity to the growth surface and high incorporation efficiency in the film. Table 1 summarizes the emission wavelength and their relative emission/incorporation efficiency.

Table I. Emission wavelengths and relative emission / incorporation efficiency of N<sub>2</sub>, O<sub>2</sub>, and H<sub>2</sub>O

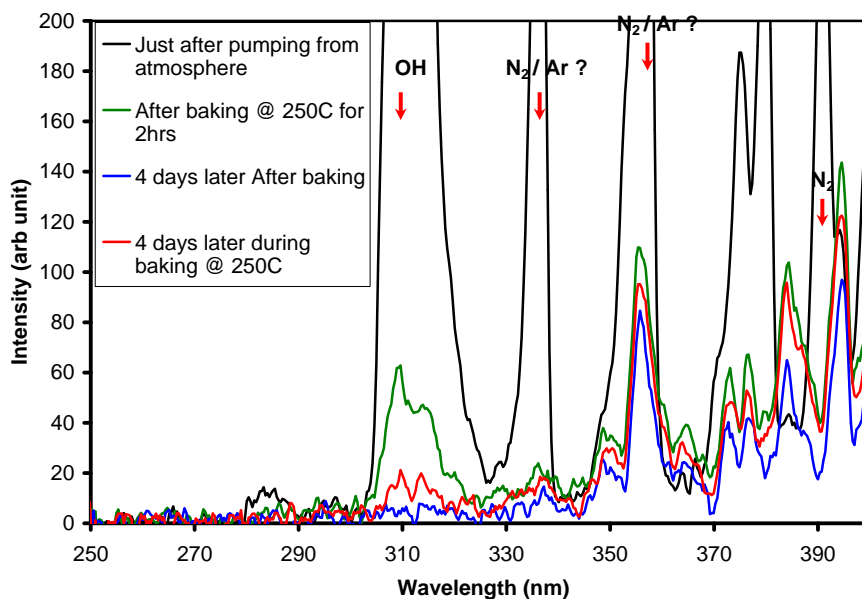
	Wavelength (nm)	Comments
N <sub>2</sub>	316, 337, 358	High emission sensitivity & low incorporation efficiency. 1000 ppm gaseous N <sub>2</sub> $\approx$ 100 ppm N in film.
O <sub>2</sub>	<200 and >750 SiO: 220 - 260	Weak emission, extreme reactivity & high incorporation efficiency. 0.1% O <sub>2</sub> in discharge $\approx$ 40% in film.
H <sub>2</sub> O	OH: 309	Weak emission band.

We performed the OES studies in the a-Si:H i-layer deposition chamber using DC plasma with various different gases (Ar, H<sub>2</sub> and SiH<sub>4</sub>). The O<sub>2</sub> emission peaks are beyond the limit of our current OES spectrometer, so we focused on the wavelength range of 250 – 400 nm to observe any possible emission from N<sub>2</sub>, H<sub>2</sub>O and SiO. Figure 5 shows the plasma emission spectra from Ar, H<sub>2</sub> and SiH<sub>4</sub> using identical gas flows and plasma parameters. The Ar emission spectra exhibits a small peak at 316 nm corresponding to N<sub>2</sub> emission and the other two peaks at 337 and 358 nm overlaps with Ar emission lines. However, the absence of any N<sub>2</sub> peaks for H<sub>2</sub> and SiH<sub>4</sub> plasma suggests that any possible atmospheric leak in the chamber is beyond the detection limit of OES and our current Ar gas may have trace amounts of N<sub>2</sub> impurities. Our a-Si:H i-layers are not deposited using Ar in the gas mixture and hence it can not be the cause of the high impurity level in our a-Si:H films.



**Figure 5. OES spectra of Ar (Black), H<sub>2</sub> (Red) and SiH<sub>4</sub> (Blue) DC plasma with identical gas flows and plasma parameters**

The OES spectra of Ar plasma was obtained at different conditions of the deposition chamber. The deposition chamber was exposed to atmosphere and then pumped down. Figure 6 shows the OES measured immediately after pump-down, after baking for 2 hrs at 250°C, after 4 days under vacuum at 100°C, and finally after raising the temperature to 250°C again. Immediately after pumping down from atmosphere, the initial OES spectra of Ar plasma shows a large peak of OH together with the other N<sub>2</sub> peaks from outgassing of the chamber. The OH peak intensity reduces after baking the chamber at 250°C for 2 hours and becomes undetectable after 4 days of pumping. This suggests there is not a significant leak. However, the increase of chamber temperature to 250°C after 4 days of pumping shows reappearance of OH peaks, indicative of outgassing of the chamber at higher temperature even after an extensive bake out and pumping cycle.



**Figure 6. OES spectra of Ar DC plasma at various conditions of deposition chamber**

Best regards,

Robert W. Birkmire  
Director

CC: Paula Newton, IEC  
Susan Tompkins, RGS  
Carolyn Lopez, NREL